Unravelling the Particulate Matter & Air Quality Index at Anand Vihar, Delhi: Trends, Exceedances and Meteorological Influences

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Abstract

Air pollution is a significant environmental concern in Delhi, consistently jeopardizing human health due to high concentrations of pollutants that frequently exceed the WHO and NAAQS limits in India. Anand Vihar is a well-known hotspot for localized air pollution and is often at the most hazardous end of the pollution spectrum. In this study, a quantitative analysis of PM_{10}, $PM_{2.5}$, and AQI, along with meteorological parameters, was conducted over 6 years (2019-2024) at Anand Vihar, Delhi. The annual and daily concentrations of PM_{10} and $PM_{2.5}$ exceed the NAAQS by 3-4 times. The inter-annual average concentrations of PM_{10} and $PM_{2.5}$ were highest in 2022 and 2024, respectively, and lowest in 2020. The overall order of seasonal average concentrations of $PM_{2.5}$ and PM_{10} ($\mu g\ m^{-3}$) was: post-monsoon ≈ winter > pre-monsoon > monsoon. The annual $PM_{2.5}/PM_{10}$ ratios were highest in 2020 and lowest in 2022, suggesting a mixture of fine and coarse-mode combustion aerosols, which accounted for 39–55% of the total $PM_{2.5}$ load. A strong correlation (>0.6) between $PM_{2.5}$ and PM_{10} was observed, indicating the prevalence of fine particulate emissions. The annual AQI values have consistently fallen into the Poor category, with only a slight improvement in 2020. According to the exceedance factor, 2024 was the most polluted year, while 2020 was the least polluted. This study underpins the limitations of current management strategies to achieve long-term outcomes for better air quality. It underlines the importance of enforcing strict curbs on

emissions from different sources, which assists in strengthening localized air-quality assessment to implement more effective strategies.

Key Words: *$PM_{2.5}$, PM_{10}, AQI, CPCB, Exceedance Factor, $PM_{2.5}/PM_{10}$*

Introduction

Air pollution is generally considered a contemporary phenomenon that is becoming worse day by day (Colbeck & Lazaridis, 2010). With the rapid increase in urbanization, atmospheric particles have become one of the most significant factors influencing urban air pollution (Ren-Jian et al., 2012). The term 'Urban Air Quality' is broad and encompasses social, economic, and health aspects across different parts of the world. An urban region refers to towns or cities where human settlement and its activities are very high. Therefore, the urban region exhibits high levels of pollution from human activities and development, which affect the environment and health. With increasing global economic growth, environmental pollution has become increasingly severe, especially inhalable particle pollution (Yan et al., 2022).

Air pollution has become a major global environmental and public health challenge — roughly 92% of the world's population lives in areas where pollutant levels exceed the World Health Organization (WHO) guidelines (Masood & Ahmad, 2021; Rautela & Goyal, 2024; WHO, 2017). One of the most prominent airborne pollutants, particulate matter (PM), has detrimental impacts on air quality and visibility, precipitation patterns, snow albedo, human health, and the global climate, as well as the Earth's radiation spectrum (Rai et al., 2021). This extensive exposure contributes significantly to health problems such as respiratory illness, cardiovascular disease, and premature death (Du et al., 2016; Kim et al., 2017; Peter et al., 2005; Callén et al., 2011; Rai et al., 2020; Bhuyan et al., 2025). According to the WHO report (Data, 2023), air pollution is responsible for 1 in 10 premature deaths, causing approximately 7 million deaths annually worldwide, and is the fourth leading cause of mortality nationwide (Rautela & Goyal, 2024). Approximately 6.7 million people died worldwide in 2019 because of indoor and outdoor air pollution. About 12.5% of all deaths in India alone were caused by air pollution, with states like Delhi, Punjab, Uttar Pradesh, and Haryana enduring a significantly larger share of the illness burden (Sekar et al., 2025).

Atmospheric aerosols, notably black carbon, particulate matter (PM_{10} and $PM_{2.5}$), dust, and sulphates, are key contributors to air quality, impacting human health and the environment (WHO, 2013), and play an important role in the global climate system (IPCC, 2013). These impacts, which have been widely investigated in South and Southeast Asia over the last two decades, are heavily influenced by the spatiotemporal variability and composition of these aerosols. The spatiotemporal variability and characteristics of these aerosols significantly impact these effects, which have been thoroughly investigated across South and Southeast Asia over the last two decades.

India, home to roughly 17.76% of the world's population, faces significant environmental challenges because many of its major cities, including Delhi, Mumbai, and Kolkata, are frequently listed among the world's most polluted cities (Rautela & Goyal, 2024). Aerosols account for 30-70% of fine particulate ($PM_{2.5}$) pollution in urban areas of India, a problem exacerbated by rapid population growth, unplanned urbanization, and industrial development. According to successive editions of the World Air Quality Report (2020-2024), Delhi has repeatedly held the unwanted distinction of being the world's most polluted national capital. Therefore, this paper seeks to evaluate the spatial and temporal variations in particulate pollution and the Air Quality Index (AQI) in one of Delhi's major pollution hotspots. The primary objective of this quantitative study is to analyse the annual and seasonal fluctuations in PM_{10} and $PM_{2.5}$ concentrations at Anand Vihar, Delhi, to identify the anthropogenic factors contributing to the city's declining air quality.

Materials & Methods

Study Area: Anand Vihar, Delhi

The National Capital Territory of Delhi (NCT) has emerged as one of India's most densely populated and rapidly growing megacities, with a population of approximately 16.78 million in 2011 and an average density of 11,297 persons/km² (https://www.census2011.co.in/).

As a landlocked region, it attracts people and development from across the country. Geographically, Delhi lies at about 28.61 °N, 77.23 °E, south of the Himalayas, on the Indo-Gangetic Plain, north of the heated plains, and east of the Thar Desert (Shankar & Gadi, 2022). According to the Indian Meteorological

Department (IMD), Delhi experiences four different seasons: summer or pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November), and winter (December to February). Generally, the weather in Delhi in the summer (pre-monsoon) is hot and dry (47°C), whereas in winter it is frigid (~3°C).

Figure 1

Study Area of Anand Vihar, Delhi

Source: Google Map

Anand Vihar (28.6502° N, 77.3027° E), situated in eastern Delhi, is a significant pollution hotspot influenced by its proximity to highways, industrial zones, and dense residential areas. Formerly primarily residential, it has been transformed into an extensive industrial and commercial hub, with a growing population density and substantial traffic due to its proximity to the Yamuna River and major highways. High levels of $PM_{2.5}$, PM_{10}, NO_x, SO_2, CO, and O_3 are caused by a variety of pollution sources, including garbage burning, small-scale industries, and automobile exhaust, all of which are influenced by the socio-economic disparity of the area (Jakhar et al., 2025).

Table 1

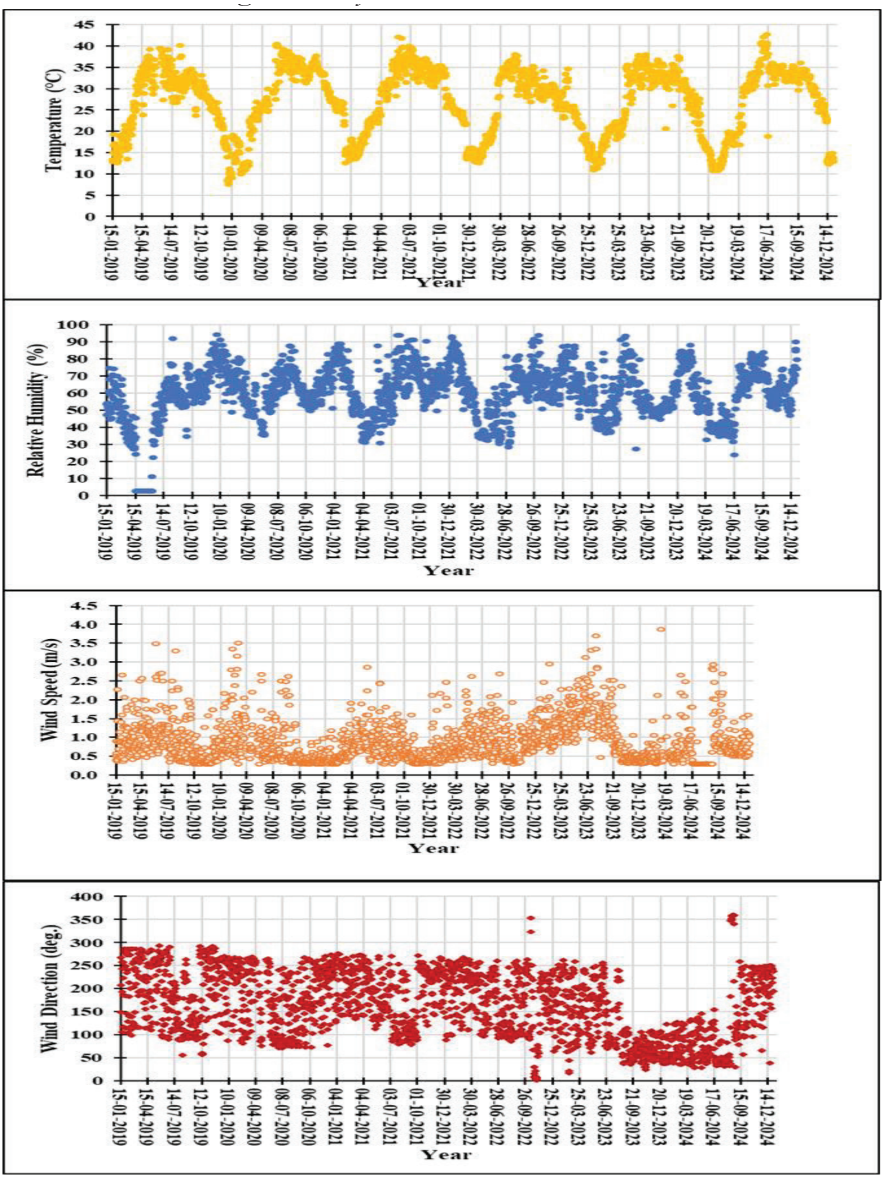
Annual and Seasonal Meteorological Parameters (Temperature, Relative Humidity, Wind Speed, Wind Direction) During the Study Period From 2019 to 2024

Years	Meteorological Parameters	Annual	Seasons			
			Winter	Pre-Monsoon	Monsoon	Post-Monsoon
2019	Temperature (°C)	26.91 ± 7.37	16.70 ± 3.10	29.54 ± 5.93	32.53 ± 3.37	27.66 ± 2.33
	Relative humidity (%)	49.29 ± 22.95	64.21 ± 13.05	21.73 ± 19.72	52.00 ± 17.13	63.71 ± 5.52
	Wind Speed (ms^{-1})	0.92 ± 0.55	0.81 ± 0.48	1.05 ± 0.43	1.12 ± 0.64	0.49 ± 0.26
	Wind Direction (deg.)	193.68 ± 67.06	212.70 ± 60.53	224.33 ± 52.24	149.60 ± 55.99	207.88 ± 72.37
2020	Temperature (°C)	27.19 ± 8.70	15.70 ± 5.20	26.12 ± 5.45	35.36 ± 1.64	29.20 ± 3.34
	Relative humidity (%)	64.20 ± 10.37	71.58 ± 8.00	56.48 ± 11.92	65.83 ± 8.32	58.52 ± 5.38
	Wind Speed (ms^{-1})	0.81 ± 0.58	0.86 ± 0.62	1.16 ± 0.66	0.79 ± 0.51	0.40 ± 0.12
	Wind Direction (deg.)	180.55 ± 63.04	211.85 ± 56.21	191.22 ± 62.45	143.22 ± 56.05	196.60 ± 49.41
2021	Temperature (°C)	28.02 ± 7.51	17.82 ± 3.33	28.60 ± 5.20	35.06 ± 2.26	27.97 ± 4.04
	Relative humidity (%)	63.32 ± 13.98	72.34 ± 8.31	47.05 ± 10.27	68.09 ± 12.30	64.17 ± 7.23
	Wind Speed (ms^{-1})	0.72 ± 0.40	0.45 ± 0.17	0.91 ± 0.42	0.89 ± 0.40	0.52 ± 0.23
	Wind Direction (deg.)	187.08 ± 54.93	210.48 ± 40.93	200.16 ± 46.53	144.84 ± 51.70	217.95 ± 37.82
2022	Temperature (°C)	26.05 ± 7.03	16.08 ± 2.02	30.65 ± 5.90	30.27 ± 2.33	25.34 ± 3.28
	Relative humidity (%)	60.81 ± 15.51	73.29 ± 10.07	45.86 ± 9.94	60.51 ± 15.34	65.65 ± 9.03
	Wind Speed (ms^{-1})	0.86 ± 0.45	0.82 ± 0.48	0.87 ± 0.44	0.94 ± 0.46	0.71 ± 0.34
	Wind Direction (deg.)	175.68 ± 64.00	192.74 ± 50.64	193.00 ± 50.40	167.18 ± 57.36	140.80 ± 91.48
2023	Temperature (°C)	26.13 ± 7.78	15.69 ± 2.62	27.16 ± 6.20	33.46 ± 2.38	26.50 ± 3.56
	Relative humidity (%)	59.12 ± 12.70	67.91 ± 10.43	53.31 ± 11.81	61.67 ± 12.93	50.21 ± 2.95
	Wind Speed (ms^{-1})	1.23 ± 0.64	0.95 ± 0.56	1.43 ± 0.40	1.63 ± 0.61	0.60 ± 0.31
	Wind Direction (deg.)	121.14 ± 64.00	129.77 ± 67.88	157.96 ± 54.05	113.10 ± 62.66	67.64 ± 20.41
2024	Temperature (°C)	27.28 ± 8.57	15.53 ± 4.27	28.98 ± 6.56	34.25 ± 2.88	29.62 ± 3.25
	Relative humidity (%)	60.33 ± 14.48	68.90 ± 11.41	43.93 ± 8.24	65.02 ± 14.30	59.77 ± 5.31
	Wind Speed (ms^{-1})	0.72 ± 0.52	0.62 ± 0.32	0.78 ± 0.63	0.75 ± 0.67	0.73 ± 0.19
	Wind Direction (deg.)	122.29 ± 80.82	118.94 ± 72.56	76.14 ± 32.01	117.97 ± 96.65	194.41 ± 49.28

± Standard Deviation

Figure 2

Meteorological Parameters During the Study Period 2019-2024



Methodology & Data Analysis

The Continuous Ambient Air Quality Monitoring System (CAAQMS) of the Central Pollution Control Board (CPCB), New Delhi, provided continuous datasets for the AQI, particulate matter (PM_{10} and $PM_{2.5}$), temperature, relative humidity, wind speed, and wind direction for the 6 years from January 2019 to December 2024. To evaluate regional and temporal fluctuations in pollution levels, data from multiple years were combined, annual averages were calculated, and daily pollutant concentrations were examined at Anand Vihar, one of the CPCB monitoring stations.

The AQI is a method for efficiently and clearly conveying air quality to the general public. It simplifies complex air quality data from multiple pollutants into a single numeric value and a corresponding colour code. The AQI levels ranged from 0 to 500, as per the National Air Quality Index of the CPCB, Ministry of Environment, Forest & Climate Change (MoEF&CC), Government of India. This range is divided into several categories of air quality indicators, each denoted by a distinct colour and associated with possible effects on human health: 0-50 (category 1), 51-100 (category 2), 101-200 (category 3), 201-300 (category 4), 301-400 (category 5), and 401-500 (category 6) representing the air quality as good, satisfactory, moderate, poor, very poor and severe, respectively. The AQI categories and ranges, along with their health impacts, are shown for reference (Table 1).

Table 2

CPCB Prescribes Different Categories of AQI and Their Health Impacts

AQI Value	AQI Category	Colour Code	Health Impacts
0 – 50	Good	Light Green	Minimal impact
51 – 100	Satisfactory	Green	Minor breathing discomfort to sensitive people
101 – 200	Moderate	Yellow	Breathing discomfort for people with lung diseases, asthma, and heart diseases
201 – 300	Poor	Orange	Breathing discomfort to most people on prolonged exposure
301 – 400	Very Poor	Red	Respiratory illness on prolonged exposure
401 – 500	Severe	Maroon	Affects healthy people and seriously impacts those with existing diseases

Source: https://www.pib.gov.in/newsite/printrelease.aspx?relid=110654

A time-series analysis using a least-squares trend line was employed to examine pollution trends and levels over the study period, which were subsequently illustrated in bar graphs to depict pollution variations in Anand Vihar, Delhi. Based on the National Ambient Air Quality Standards (NAAQS), the pollution trends for 2019–2024 were analysed. By formulating a straight-line equation, Y = a + bX, where a and b are constants that indicate the relationship between the variables and help forecast future values, this method is quite successful at identifying long-term trends.

Additionally, the Exceedance Factor (EF) method (Equation 1), adopted by CPCB, was applied to evaluate temporal variations in air quality (Firdaus, 2010; Haque et al., 2017). The EF is the ratio of the annual average concentration of a pollutant to its corresponding regulatory standard of the NAAQS. According to EF values, air quality was classified as low, moderate, high, or critical.

EF of the $PM_{2.5}$ and PM_{10} is calculated using the following formula:

$$EF = \frac{\textit{Observed annual mean concentration of } PM_{10} \ \& \ PM_{2.5}}{\textit{Annual air quality standard of } PM_{10} \ \& \ PM_{2.5}} \qquad \text{(Equation 1)}$$

According to the EF values, there are four categories of air pollution:

1. Critical pollution (CP): when the EF value is equal to or more than 1.5;

2. High pollution (HP): when the EF value lies between 1.0 and 1.5;

3. Moderate pollution (MP): when the EF value lies between 0.5 and 1.0;

4. Low pollution (LP): when the EF value is equal to or less than EF 0.5

The EF compares the measured concentrations to Indian standards (NAAQS) to categorize pollution as low, moderate, high, or critical. It is a better indicator of how bad the air is than pollutant levels alone. When EF is identified as moderate, high, or critical, the pollutant is above the permitted limit, albeit to varying degrees, and poses a severe threat to people and the environment, requiring urgent action. On the contrary, a low EF category indicates that the pollutant is within the standards but may exceed them soon, necessitating preventive actions to maintain control (Sharma et al., 2019; Roy & Singha, 2020).

Results & Discussion

In this study, levels of ambient particulate pollutants, AQI, and meteorological parameters were compared across the pre-COVID-19, COVID-19, and post-COVID-19 periods from 2019 to 2024. The annual and seasonal meteorological parameters, such as temperature (°C), relative humidity (%), wind speed ($m\ s^{-1}$), and wind direction (deg.), are shown in Table 2 for the study period from 2019 to 2024. Fig. 2 depicts the trend of all meteorological parameters from 2019 to 2024. Table 3 shows the observed annual and seasonal variation of PM_{10}, $PM_{2.5}$, and AQI during the study period from 2019 to 2024. In comparison, the data revealed a significant decrease in PM levels before, during, and after the lockdown.

Annual Variation of PM_{10} and $PM_{2.5}$

Fig. 3 depicts the time-series analysis of PM_{10} and $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) during the study period from 2019 to 2024. Fig. 4 illustrates the year-wise trends in the annual mean concentrations of PM_{10} and $PM_{2.5}$ ($\mu g\ m^{-3}$), represented as bar graphs. The order of inter-annual average concentrations of $PM_{2.5}$ ($\mu g\ m^{-3}$) was: 2024 (~136) > 2021 (~129) > 2019 (~128) = 2023 (~128) > 2022 (~124) > 2020 (~115) and PM_{10} ($\mu g\ m^{-3}$) was: 2022 (~317) > 2024 (~314) > 2023 (~297) > 2021 (~274) > 2019 (~272) > 2020 (~206). Although the concentrations varied somewhat between years, the general trend shows that PM levels continually exceeded the NAAQS of India, i.e., 40 $\mu g\ m^{-3}$ for $PM_{2.5}$ and 60 $\mu g\ m^{-3}$ for PM_{10}, emphasizing ongoing air quality concerns throughout the study period. According to inter-annual trends, significant declines in PM_{10} and $PM_{2.5}$ concentrations were observed in 2020 compared to 2019, with reductions of almost 25% and 11%, respectively. The results showed consistency with a decrease in human-driven activities such as vehicular traffic and industrial activities during the COVID-19 lockdown period. However, after 2021, PM levels rose, suggesting that the decline was only transitory and that PM pollution remains predominantly attributable to anthropogenic activities.

Figure 3

The Time Series of Yearly Concentration of PM_{10} and $PM_{2.5}$ ($\mu g\ m^{-3}$) During the Study Period 2019-2024.

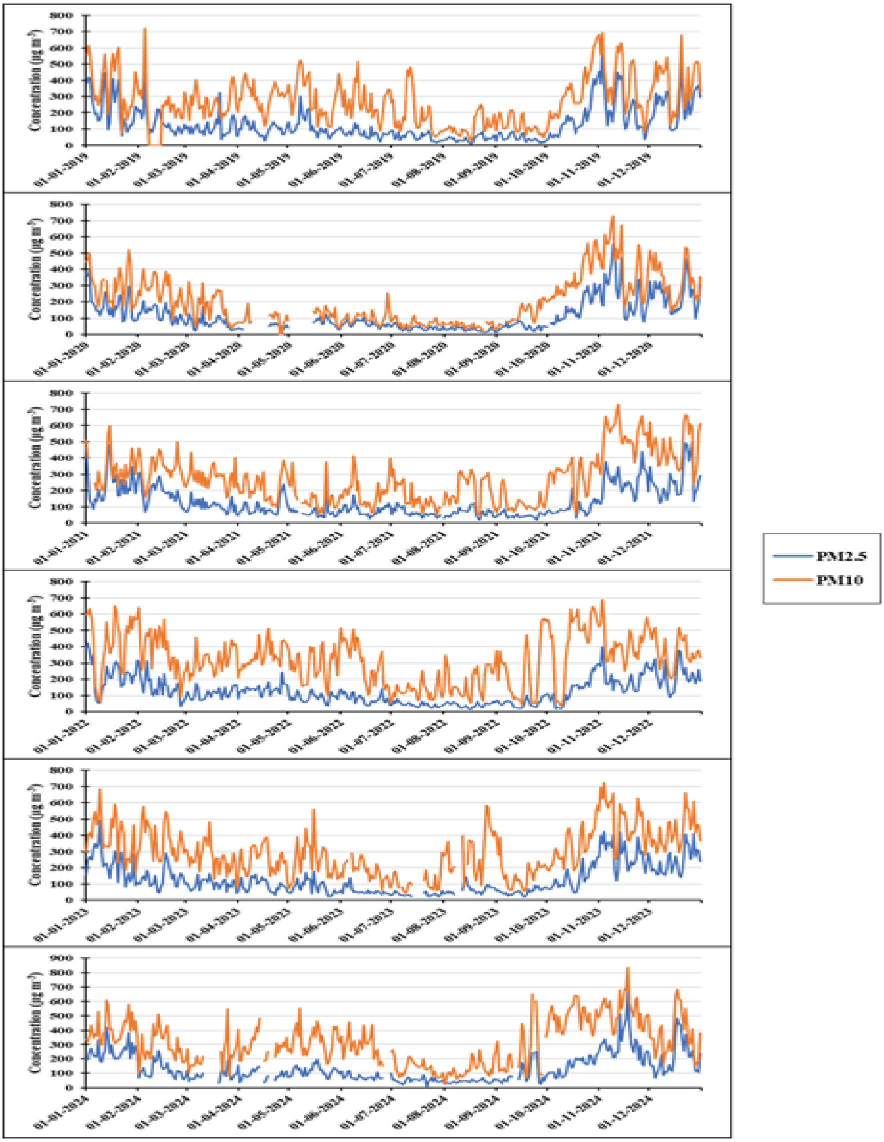


Table 3

The Annual and Seasonal Variation of PM_{10}, $PM_{2.5}$, and AQI During the Study Period from 2019 to 2024

Year	Annual		Winter		Pre-Monsoon		Monsoon		Post-Monsoon	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
2019	272.40 ± 144.58	128.48 ± 104.69	351.13 ± 140.60	209.77± 108.58	281.37 ± 93.41	105.55 ± 50.50	171.97 ± 104.92	52.93 ± 25.48	353.91 ± 161.38	194.26 ± 130.76
2020	206.39 ± 149.48	114.57 ± 99.58	298.05 ± 105.39	183.25± 88.83	135.10 ± 70.63	64.52 ± 30.69	86.77 ± 46.51	44.41 ± 20.46	381.64 ± 144.30	205.62 ± 117.72
2021	274.02 ± 148.28	128.69 ± 97.16	380.73 ± 117.40	228.21± 98.86	218.55 ± 89.20	89.75 ± 45.77	168.00 ± 82.73	62.99 ± 27.47	413.98 ± 149.11	169.61 ± 100.72
2022	317.32 ± 153.47	124.15 ± 83.59	391.52 ± 138.19	202.42± 85.48	314.50 ± 83.87	111.97 ± 35.33	210.40 ± 132.29	53.96 ± 26.69	425.91 ± 158.45	167.42 ± 82.99
2023	296.63 ± 146.63	127.87 ± 94.94	395.38 ± 109.94	203.54± 88.49	252.44 ± 91.43	90.77 ± 36.64	189.55 ± 110.80	54.13 ± 22.99	408.94 ±147.65	207.52 ± 106.05
2024	313.69 ± 158.91	136.04 ± 100.95	351.94 ± 121.79	196.28± 97.88	287.34 ± 99.52	100.34 ± 36.65	190.56 ± 115.37	62.89 ± 37.44	519.52 ± 95.63	228.51 ± 116.21

± Standard Deviation

Figure 4

The Inter-Annual Concentration of PM_{10} and $PM_{2.5}$ (μg m^{-3}) During the Study Period 2019-2024

Seasonal Variation of PM_{10} and $PM_{2.5}$

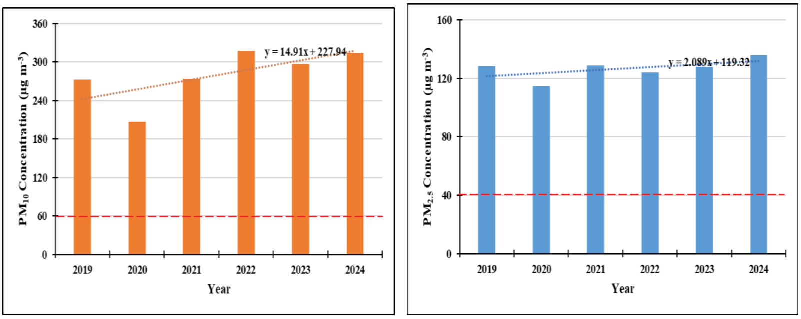
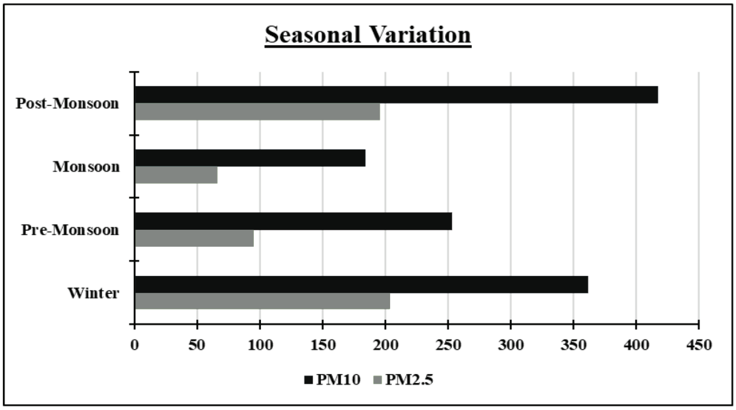


Figure 5

The Seasonal Variation of PM_{10} and $PM_{2.5}$ (μg m^{-3}) During the Study Period 2019-2024

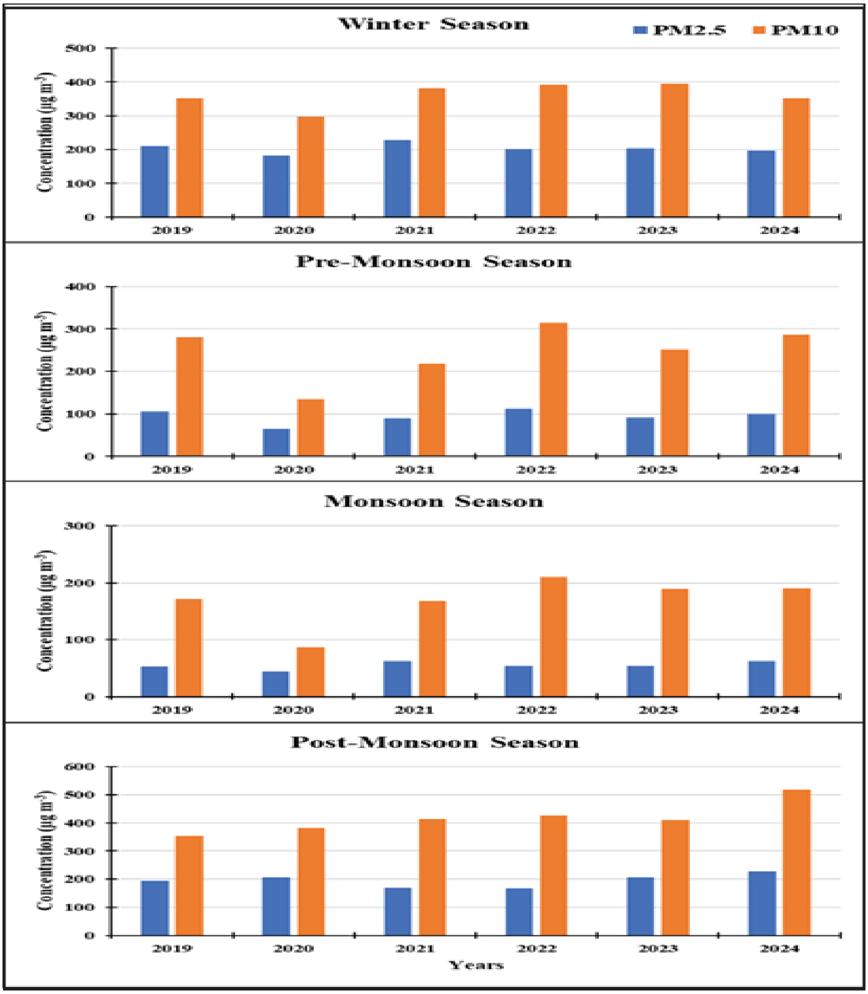


During the six-year study period, the overall order of seasonal average concentrations of PM_{10} was found to be: post-monsoon (417.32 μg m^{-3}) > winter (361.49 μg m^{-3}) > pre-monsoon (252.96 μg m^{-3}) > monsoon (183.94 μg m^{-3}); and PM2.5: winter (203.86 μg m^{-3}) > post-monsoon (195.46 μg m^{-3}) > pre-monsoon

(95.33 µg m^{-3}) > monsoon (66.10 µg m^{-3}). The overall order of seasonal average concentrations of $PM_{2.5}$ and PM_{10} (µg m^{-3}) was: post-monsoon ≈ winter > pre-monsoon > monsoon. A similar trend was observed in various studies, like Dhaka et al. (2024), Chetna et al. (2022), Singh et al. (2020), Sharma et al. (2018), and Tiwari et al. (2015).

Figure 6

The Interannual Concentrations of PM_{10} and $PM_{2.5}$ (µg m^{-3}) During the Winter, Pre-Monsoon, Monsoon, and Post-Monsoon Seasons from 2019-2024



During winters, the inter-annual trend of PM_{10} concentrations was recorded as 2023 > 2022 > 2021 > 2024 > 2019 > 2020; whereas for $PM_{2.5}$, the concentration was observed as 2021> 2019> 2023> 2022 > 2024 > 2020. According to meteorological "deweathing" studies for Delhi by Verma et. al. (2025), winters tend to elevate and reduce $PM_{2.5}$ and PM_{10} by around 17 µg m^{-3} and 7.8 µg m^{-3}, respectively. It suggests that year-round weather changes, such as variations in inversion strength, changes in boundary-layer height, biomass burning, and lower wind speeds, influence particulates in distinct ways. Jain et al. (2020) indicated that during winters, $PM_{2.5}$ is predominantly affected by local biomass and stubble burning, while PM_{10} comprises a greater proportion of dust from local re-suspension activities, including construction and pavement dust. The lowest concentration of pollutants was observed in 2020, likely attributable to COVID-19 lockdowns that reduced construction activity and traffic, leading to a decline in pollutants influenced by regional emissions and transport.

During the pre-monsoon period, the peak concentrations recorded in 2022 for both PM_{10} and $PM_{2.5}$ were probably due to a swift resurgence of unrestrained anthropogenic activities, coupled with adverse meteorological conditions such as reduced wind speeds or elevated temperatures that promote atmospheric accumulation and the formation of secondary aerosols. The observed PM_{10} trend (2022 > 2024 > 2019 > 2023 > 2021 > 2020) varies with the $PM_{2.5}$ trend (2022 > 2019 > 2024 > 2023 > 2021 > 2020), which is mainly driven by emissions from combustion sources such as vehicular or industrial, because the pre-monsoon season typically has higher temperatures and a lower level of relative humidity.

During the monsoon, the inter-annual trend of PM_{10} concentrations was recorded as 2022 > 2024 > 2023 > 2019 > 2021 > 2020; whereas for $PM_{2.5}$, the concentration was observed as 2021 > 2024 > 2023 > 2022 > 2019 > 2020. The fundamental reason for such reduced concentrations during the monsoon season is the mechanism of wet accumulation of particulate matter and the effective washing of pollutants by precipitation (Singh et al., 2020; Murari et al., 2017).

During the post-monsoon season, the inter-annual trend of PM_{10} concentrations was recorded as 2024 > 2022 > 2021 > 2023 > 2020 > 2019; whereas for $PM_{2.5}$, the trend was 2024 > 2023 > 2020 > 2019 > 2021 > 2022. PM_{10} is highly fluctuating because it is primarily driven by local emission sources such as road dust, construction, and industrial smoke, which explained its highest concentrations in 2024 and 2022, when activity related to construction, dry weather, and dust re-suspension was elevated, while lower levels in 2019-2020 illustrate stricter regulations and COVID-19 restrictions. However, $PM_{2.5}$ concentrations are highest in 2024 and 2023 due to regional combustion processes such as stubble burning in Punjab, U.P., and Haryana, secondary aerosol formation, and urban emissions, particularly under low wind speeds and low mixing layers. One notable finding was that $PM_{2.5}$ levels in 2022 contributed the least to fine-mode pollution, even lower than in 2020, while PM_{10} levels in 2022 contributed significantly to coarse-mode pollution. This disparity may be explained by the fact that while regional combustion-related sources of $PM_{2.5}$, particularly stubble burning in Punjab and Haryana, were comparatively weaker in 2022, intense local activities like construction, re-suspension of road dust, and industrial smoke contributed significantly to coarse particles.

Table 4

The Annual and Seasonal Values of the $PM_{2.5}/PM_{10}$ Ratio During the Study Period from 2019 to 2024

Year	Annual	Winter	Pre-Monsoon	Monsoon	Post-Monsoon
2019	0.43 ± 0.16	0.60 ± 0.12	0.38 ± 0.15	0.33 ± 0.08	0.51 ± 0.13
2020	0.55 ± 0.16	0.60 ± 0.15	0.47 ± 0.18	0.56 ± 0.18	0.50 ± 0.16
2021	0.45 ± 0.15	0.60 ± 0.14	0.42 ± 0.11	0.40 ± 0.11	0.39 ± 0.15
2022	0.39 ± 0.14	0.52 ± 0.13	0.36 ± 0.08	0.30 ± 0.12	0.40 ± 0.12
2023	0.41 ± 0.15	0.50 ± 0.13	0.36 ± 0.09	0.33 ± 0.16	0.48 ± 0.11
2024	0.43 ± 0.17	0.54 ± 0.13	0.37 ± 0.19	0.37 ± 0.14	0.43 ± 0.16

± Standard Deviation

Table 5

The Annual and Seasonal Values of AQI During the Study Period from 2019 to 2024

Year	Annual		Winter		Pre-Monsoon		Monsoon		Post-Monsoon	
	AQI Value	AQI Category	AQI Value	AQI Category	AQI Value	AQI Category	AQI Value	AQI Category	AQI Value	AQI Category
2019	239	Poor	325	Very Poor	236	Poor	149	Moderate	308	Very Poor
2020	217	Poor	320	Very Poor	149	Moderate	117	Moderate	321	Very Poor
2021	248	Poor	355	Very Poor	198	Moderate	156	Moderate	328	Very Poor
2022	273	Poor	341	Very Poor	271	Poor	185	Moderate	344	Very Poor
2023	258	Poor	344	Very Poor	216	Poor	172	Moderate	332	Very Poor
2024	272	Poor	328	Very Poor	246	Poor	165	Moderate	394	Very Poor

Table 6

The Annual Exceedance Factor of PM_{10} and $PM_{2.5}$ During the Study Period from 2019 to 2024

Year	Annual		Number of days							
			Critical Pollution (CP)		High Pollution (HP)		Moderate Pollution (MP)		Low Pollution (LP)	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
2019	2.1	3.2	281	182	35	88	39	70	2	25
2020	1.9	2.9	185	149	39	53	85	93	55	71
2021	2.1	3.2	266	180	55	84	37	58	7	11
2022	2.1	3.1	297	213	31	59	34	63	3	30
2023	2.1	3.2	295	188	30	61	26	93	14	23
2024	2.3	3.4	281	193	35	69	25	78	25	26

$PM_{2.5}/PM_{10}$ Ratio & its Correlation

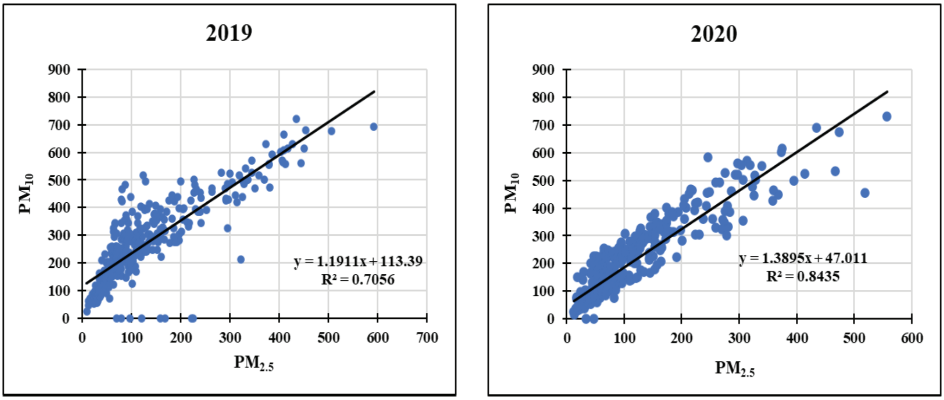
The $PM_{2.5}/PM_{10}$ ratios showed significant seasonal variation when examined to assess particle-size effects. This variation could be explained by the chemical composition of aerosols, which varies depending on natural, human-driven, and meteorological factors. The annual and seasonal values of the $PM_{2.5}/PM_{10}$ ratio during the study period from 2019 to 2024 shown in Table 4. While smaller $PM_{2.5}/PM_{10}$ ratios (<0.5) indicate the presence of more coarse-sized particles in particle pollution, primarily emitted/generated from natural sources like long-distance transport sand, soil and fugitive dust, re-suspension of road dust from construction and agricultural activities; higher $PM_{2.5}/PM_{10}$ ratios >0.5) indicate the predominance of fine particles contributed by anthropogenic sources like vehicular exhaust, industrial processes, burning of biomass, and the production of secondary aerosols (Drăgoi et al., 2025; Tiwari et al., 2015; Bamola et al., 2024; Fatima et al., 2022).

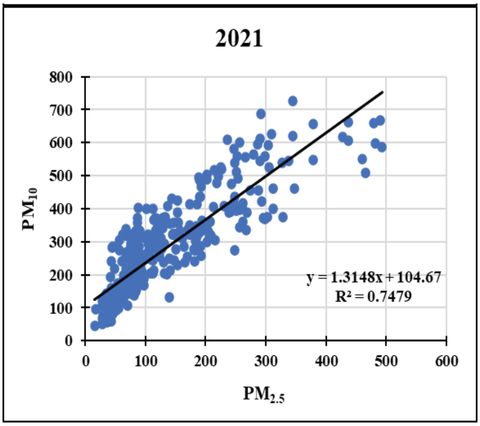
The annual $PM_{2.5}/PM_{10}$ ratios ranged from 0.39 to 0.55, with the highest ratio in 2020, followed by 2021, 2019, 2024, 2023, and 2022. It suggests a mixture of both fine- and coarse-mode combustion aerosols, which constituted 39–55% of respirable fine particles and total PM, posing a significant health risk. The highest annual average was observed in 2020, indicating fewer coarse-particle emissions despite pandemic-induced restrictions and the continued presence of emissions from combustion sources. Seasonally, significant variation in the $PM_{2.5}/PM_{10}$ ratio was observed at 0.50-0.60 (winter), 0.36-0.47 (pre-monsoon), 0.30-0.56 (monsoon), and 0.39-0.51 (post-monsoon), indicating distinct patterns influenced by meteorology and emissions processes. Lower $PM_{2.5}/PM_{10}$ ratios (< 0.40) were observed during the pre-monsoon and monsoon seasons, predominantly influenced by crustal sources and wind-driven dust from the re-suspension of road dust, construction activities, and industrial emissions, while rainfall effectively scavenges fine particles. A recent study of Tiwari et al. (2025) reported similar observations across 17 monitoring stations in Delhi and Haryana. On the contrary, higher ratios (> 0.55) were reported during the winter and post-monsoon seasons, reflecting contributions from fine particulates emitted by stubble burning in neighbouring regions, biomass burning, residential heating, vehicular emissions, and secondary aerosol formation. A consistently high $PM_{2.5}/PM_{10}$ ratio recorded throughout winter from 2019-2024, favouring entrapment of fine particles due to low boundary layer height emitted by human activities such as automotive exhaust, residential heating, power plants, biomass burning, and industries (Singh et al., 2013). Furthermore, due to stagnant atmospheric conditions in the post-monsoon season, deposition (wet and dry) of aerosols contributes to the accretion of $PM_{2.5}$, which ultimately leads to the formation of secondary aerosols in the atmosphere. Similar observations were reported by Fatima et al. (2022) at three sites: Alipur (residential), Okhla (industrial), and Pusa Road (traffic).

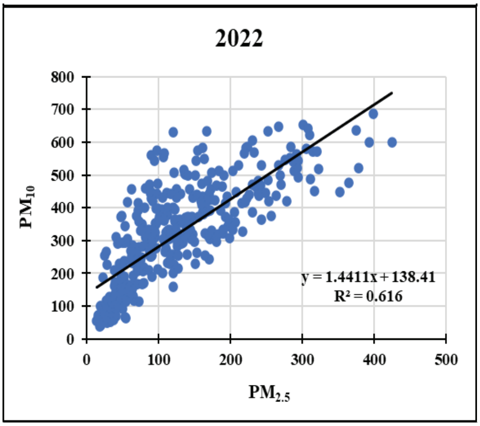
Overall, the observed order of correlation between $PM_{2.5}$ and PM_{10} in 2019, 2020, 2021, 2022, 2023, and 2024 was 0.84 (2020) > 0.76 (2023) > 0.75 (2021) > 0.71 (2019) > 0.68 (2024) > 0.62 (2022). A strong correlation between 0.6 and 0.8 of both pollutants ($PM_{2.5}$ and PM_{10}) was observed, showing the prevalence of fine particulates at the study site. A strong correlation (r^2 = 0.84) was observed in 2020 between $PM_{2.5}$ and PM_{10}, suggesting that the concentrations of both pollutants are primarily dependent on emissions from vehicular exhaust, industrial sources, biomass burning, road dust, and construction activities, which are ubiquitous sources at the study site. Kumar and Priyanka (2021) also reported the good correlation between $PM_{2.5}$ and PM_{10} during 2018-2020 in Delhi.

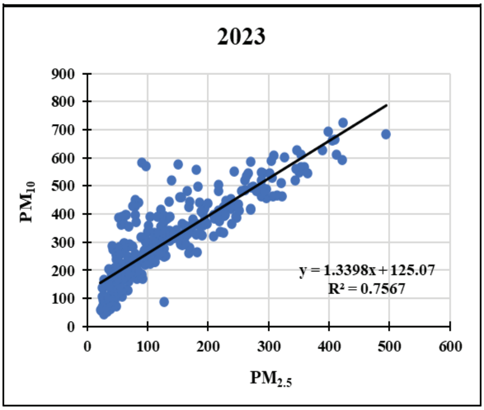
Figure 7

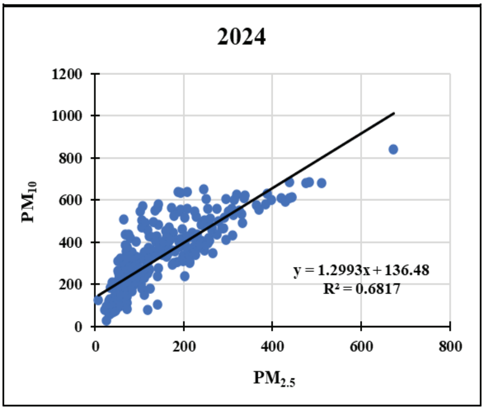
The Correlation Analysis Between $PM_{2.5}$ and PM_{10} *($\mu g\ m^{-3}$) During the Study Period from 2019 to 2024*











AQI Analysis

Comparing AQI data from 2019 to 2024, we observed significant seasonal and annual variations. The annual AQI values varied between 217 (2020) and 273 (2022) over the course of the six-year study period, consistently falling into the Poor category with only a slight improvement in 2020, which was probably due to reduced human activities during COVID-19 lockdowns, followed by an upsurge due to higher pollution levels in subsequent years. As a result, the data obtained showed that the ambient air quality of Anand Vihar, Delhi, is still worsening.

It is clearly evident from Table 5 that during winter and post-monsoon seasons, the AQI displays the most severe deteriorating air of Anand Vihar, Delhi, persistently lying in the Very Poor category (ranging from 320 (2020) to 355 (2021) during winters and 308 (2019) to 394 (2024) during post-monsoon) throughout the 6-year study period. During the pre-monsoon season, the AQI is in the Poor category, ranging from 149 (2020) to 271 (2022), except in 2020 and 2021, which may be attributed to the COVID-19 lockdowns that began in March 2020. On the contrary, the monsoon season falls within the Moderate AQI category, ranging from 117 (2020) to 185 (2022), suggesting a washout effect on pollutants.

Collectively, the data indicate that, despite yearly variations, air quality in every season—except the monsoon—remained above acceptable levels, with winter and the post-monsoon seasons posing the most significant health risks. The ongoing prevalence of Poor to Very Poor AQI categories underscores the urgent need for improved air-quality mitigation strategies, especially those that target seasonal emitters and weather factors.

Exceedance Factor (EF) of PM_{10} and $PM_{2.5}$

CPCB widely used the EF to define pollution episodes, and the intensity and severity of Delhi's persistent and severe air pollution were examined at Anand Vihar from 2019 to 2024. Table 6 shows the annual and seasonal EF of $PM_{2.5}$ and PM_{10}, along with the number of critical, high, moderate, and low pollution days. The annual EF values of PM_{10} and $PM_{2.5}$ were highest in 2024 (2.3 and 3.4, respectively) and lowest in 2020 (1.9 and 2.9, respectively), indicating 2024 as the most polluted and 2020 as the least polluted year during the 6-year study period at Anand Vihar. Both pollutants fell into the critical pollution (CP) category (EF > 1.5) during the study period, with PM_{10} EF values ranging from 1.9 to 2.3 and $PM_{2.5}$ EF values ranging from 2.9 to 3.4. The number of CP days of $PM_{2.5}$ and PM_{10} varied from 185 and 149 days in 2020, respectively, to a peak of 213 and 297 days in 2022, respectively. Long-term exposure to such severe pollution indicates long-term environmental stress in the region, which frequently worsens during winter inversions, intensive construction activities, and heavy vehicular emissions. Despite the COVID-19 lockdowns in 2020, the number of CP days of $PM_{2.5}$ remained high (149 days), indicating significant impacts from regional ambient pollution and local non-traffic sources. However, there were very few days with a low pollution (LP) category during the study period. Low-pollution days for $PM_{2.5}$ ranged from 11 in 2021 to 71 days in 2020, whereas PM_{10} persisted below 55 days in all of the years.

The lack of LP days underscores the persistent average particulate concentration, which seldom falls below standard limits. As a result, the findings suggest that prolonged exposure to such extreme PM levels has severe adverse health effects, particularly on respiratory and cardiovascular illnesses.

Conclusion

This study presents an inter-annual and seasonal progression of $PM_{2.5}$ and PM_{10} from January 2019 to December 2024, at Anand Vihar, Delhi, as follows:

- The interannual average concentrations of PM_{10} and $PM_{2.5}$ were highest in 2022 and 2024, respectively. Although the concentrations varied daily (24-hr) and between years, the general trend shows that PM levels continually exceeded the National Ambient Air Quality Standards (NAAQS) of India, emphasizing ongoing air quality concerns throughout the study period.
- During the six-year study period, the overall order of seasonal average concentrations of PM_{10} ($\mu g\ m^{-3}$) was found to be: post-monsoon (417.32 $\mu g\ m^{-3}$) > winter (361.49 $\mu g\ m^{-3}$) > pre-monsoon (252.96 $\mu g\ m^{-3}$) > monsoon (183.94 $\mu g\ m^{-3}$); and $PM_{2.5}$: winter (203.86 $\mu g\ m^{-3}$) > post-monsoon (195.46 $\mu g\ m^{-3}$) > pre-monsoon (95.33 $\mu g\ m^{-3}$) > monsoon (66.10 $\mu g\ m^{-3}$).
- The seasonal inter-annual trend of PM_{10} concentrations was recorded as highest during winter (2023 and 2021), pre-monsoon (2022 for both), monsoon (2022 and 2021), and post-monsoon (2024 for both); and lowest in 2020, except in post-monsoon (2019 for PM_{10} and 2022 for $PM_{2.5}$). It suggests that year-round weather changes, such as variations in inversion strength, changes in boundary-layer height, biomass burning, and lower wind speeds, influence particulates in distinct ways. The lowest concentration of pollutants was observed in 2020, likely attributable to COVID-19 lockdowns that reduced construction activity and traffic.

- The annual $PM_{2.5}/PM_{10}$ ratios ranged from 0.39 to 0.55, with higher ratios in 2020 and lower in 2022, suggesting a mixture of fine- and coarse-mode combustion aerosols, which accounted for 39–55% of $PM_{2.5}$ relative to total PM, a major health risk. Seasonally, significant variation in the $PM_{2.5}/PM_{10}$ ratio was observed at 0.50-0.60 (winter), 0.36-0.47 (pre-monsoon), 0.30-0.56 (monsoon), and 0.39-0.51 (post-monsoon), indicating distinct patterns influenced by meteorology and emissions processes.
- A strong correlation between 0.6 and 0.8 of both pollutants ($PM_{2.5}$ and PM_{10}) was observed throughout the study period, showing the prevalence of fine particulates at the study site. The observed interannual correlation between $PM_{2.5}$ and PM_{10} was highest in 2020 and lowest in 2022, with values of 0.84 and 0.62, respectively.
- The annual AQI values ranged from 217 (2020) to 273 (2022) over the six-year study period, consistently falling into the Poor category, with only a slight improvement in 2020, likely due to reduced human activity during COVID-19 lockdowns. Seasonally, winter and post-monsoon seasons showed higher AQI values than pre-monsoon and monsoon seasons.
- The annual EF values of PM_{10} and $PM_{2.5}$ were highest in 2024 (2.3 and 3.4, respectively) and lowest in 2020 (1.9 and 2.9, respectively), indicating 2024 as the most polluted and 2020 as the least polluted year during the 6-year study period at Anand Vihar, Delhi.

The study of air quality trends in Anand Vihar, Delhi, shows that temperature inversions, crop residue burning, and emissions from Indian festivals cause recurring pollution peaks during the winter and post-monsoon seasons, with monsoon rains offering only momentary relief. According to the findings of this study, stronger interventions, such as stricter vehicle limitations, controlling dust at construction sites, industrial emission enforcement, collaboration between regions for stubble burning mitigation, and improved transportation connectivity, are of paramount importance. In the coming decades, the burden of particulate pollution in Anand Vihar, Delhi, is expected to remain very high in the absence of targeted, sustained interventions.

Acknowledgment

The authors gratefully acknowledge the support of the Central Pollution Control Board (CPCB), Government of India, for providing access to the ambient air-quality/continuous monitoring data used in this study. The publicly available datasets furnished by CPCB have enabled analysis of air pollutant concentrations at the Anand Vihar site and the assessment of temporal and spatial trends. We also wish to thank CPCB for maintaining the data portal and for their transparency and consistency in data collection, which significantly facilitated our research. We want to acknowledge Prof. Sanjeev Kumar Tiwari, Principal, Maharaja Agrasen College, University of Delhi, for his encouragement for this work.

Funding

The authors received no financial assistance.

Conflict of interest

The authors have no conflicts of interest.

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